Second International Future Mining Conference 2011

Paper Number: 21

Mine Road Design and Management In Autonomous Hauling Operations: A Research Roadmap

RJ Thompson

Professor of Mining Engineering, Curtin University, WA School of Mines
Locked Bag 30, Kalgoorlie 6433 WA
Phone: +61 (0)8 9088 6172 Fax: +61 (0)8 9088 6151 Email: r.thompson@curtin.edu.au

ABSTRACT

In truck-based hauling systems, the mine haul road network is a critical and vital component of the production process. As such, under-performance of a haul road will impact immediately on mine productivity and costs. Operations safety, productivity and equipment longevity are all dependent on well-designed, constructed and maintained haul roads. With the advent of autonomous haul trucks, the haul road itself becomes all the more critical to the success of these type of operations; not only in relation to mine operators requirements for safer and more efficient and predictable haulage systems, but also in response to autonomous truck manufacturers' requirements for a more predictable and controlled operating environment. This paper presents a brief summary of the state-of-the-art in surface mine road design and then proceeds to examine the design and technological challenges associated providing a safe, predictable and affordable road for autonomous mine haul trucks. The paper serves as a basis for evaluating the contributions that enhancements in road design and management can deliver to autonomous mining operations, an initiative that also has scope for adoption within the operating life of many mines, haul roads and haul trucks.

INTRODUCTION

In autonomous as well as conventional mine truck-based hauling systems, the mine haul road network is a critical and vital component of the production process. As such, under-performance of a haul road will impact immediately on mine productivity and costs. Operations safety, productivity and equipment longevity are all dependent on well-designed, constructed and maintained haul roads. With increasing truck size and traffic volumes, haul road performance can be compromised, resulting in excessive total road-user costs; seen directly as an increase in cost per ton hauled and more frequent road maintenance or rehabilitation interventions, and also indirectly as reduced production rates and vehicle and component service life.

As the concept of autonomous haulage systems (AHS) moves from proto-types to production-ready applications, the operating performance of the haul road will become 'mission critical' to the overall success of autonomy in mining. Rapid deterioration of road performance will require costly remediation, human intervention and significant, albeit temporary, changes to operating procedures, to accommodate these types of events. As an example, with autonomous trucking, vehicle path wander is minimal and the road will be subject to high channelized wheel loads over a very limited (dither) area, without the wheel-path variations often encountered with conventional trucking. This effect, coupled with the need for reliable and predictable performance requirements, presents challenges in mine road structural design, materials selection, performance specifications and construction. However, with autonomous trucks and channelized traffic comes the opportunity for instance, to reduce road construction and operating width, and therefore generate potentially significantly reductions in stripping ratios and improvements to mine economics, but only if the design of the road, and it's associated deterioration rate, is predictable and manageable, based both on the materials used to construct the road and the maintenance (if any) required to be carried out on the road.

Autonomous trucking has many potential advantages over conventional trucking, and to fully leverage these benefits into the future, mine road design and management needs to develop to meet the requirements of autonomy in mining.

Autonomy Technology and the Future of Mining

The mining industry is looking into a future of increasing global demand for many of its products, but is constrained by resource grades, energy, labour, safety, environmental and capital and working-cost considerations. It could be argued that the outlook is not dissimilar to that of the previous century, it is only the level of technology that was appropriate then, as compared with now, that guides the solution strategy. Open-pit mining began in earnest in the early 1900's and led indirectly to the first dump truck patent in 1920 by Mawhinney, following which truck capacity has grown to upwards of 360t today, accompanied by a reduction in mineral grades mined, implicating larger volumes of material to be moved at increased levels of efficiency.

Associated with this trend are various technological initiatives, from early open-pits in the 1900's, the block caving methods of the 1950's, PLC's in 1970's, through to automation, autonomous vehicles, AHS and ultimately, the autonomous mine. From the start of the 21st century, mining has evolved from the idea of a 'modern' mine, to that of a 'real-time' mine and, ultimately, will evolve into an 'intelligent' mine, as discussed by Pukkila and Sarkka (2000). Figure 1 shows this evolution and the accompanying development of autonomy, from simple user-interface and monitoring development, through to more complex aspects of perception, position, navigation and mission planning technologies.

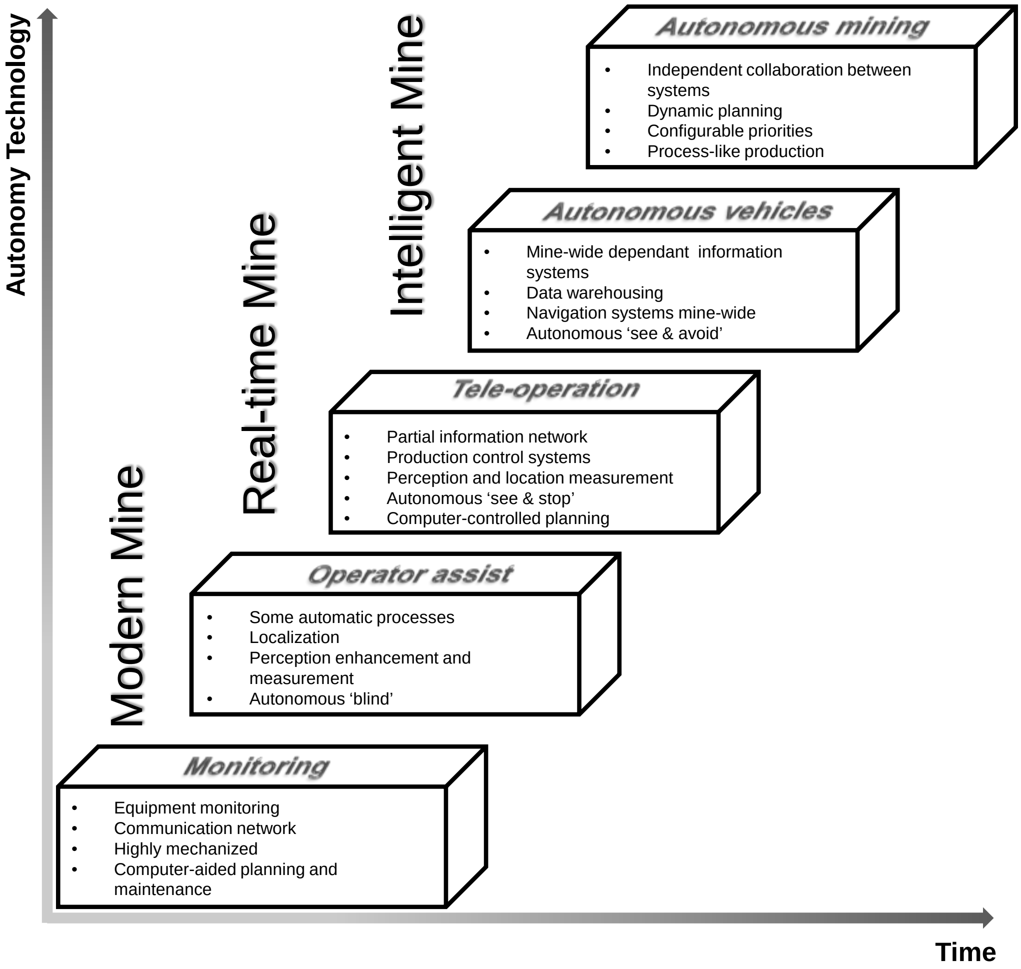

Fig 1 Incremental evolutionary phases of autonomous haulage and mining systems

The incremental approach shown in Figure 1 has some key advantages over the alternative ‘all at once’ turnkey option in which the entire haul fleet is autonomous, delivered pre-integrated by a single original equipment manufacturer (OEM) for a new mine or new fleet. Although the ‘all at once’ option offers maximum potential benefits, it has key limitations in terms of process, investment and reliability risks, together with dependence on a single OEM and inability to accommodate or expand to mixed fleets. The incremental approach, in which user-assist products transition to full autonomy over time has the benefit of lower investment and risk, and critically, less chance of technology failure due to a miss-fit between work systems (which should grow and evolve with the technology over time) being too technically advanced or simply by not recognizing and fully addressing the impact of autonomy technology on mining organizational processes. Hustralid (1998) emphasised the balance that must be sought to ensure the application of appropriate technology now, and research and innovation of new technologies based on acquired knowledge and experience, in a discrete step-wise manner. However, this approach requires that the independently developed increments are synchronized across industry to enable their adoption via a multitude of autonomy platforms (Albanese and McGagh, 2011).

Using AHS in an open pit improves safety, maintenance and equipment life, optimizes fuel consumption, and provides streamlined operations with increasingly accurate production systems. Parreira and Meech (2010) have estimated that the changes to a mines’ Key Performance Indicators (KPI’s) when this technology is adopted, as illustrated below in Figure 2.

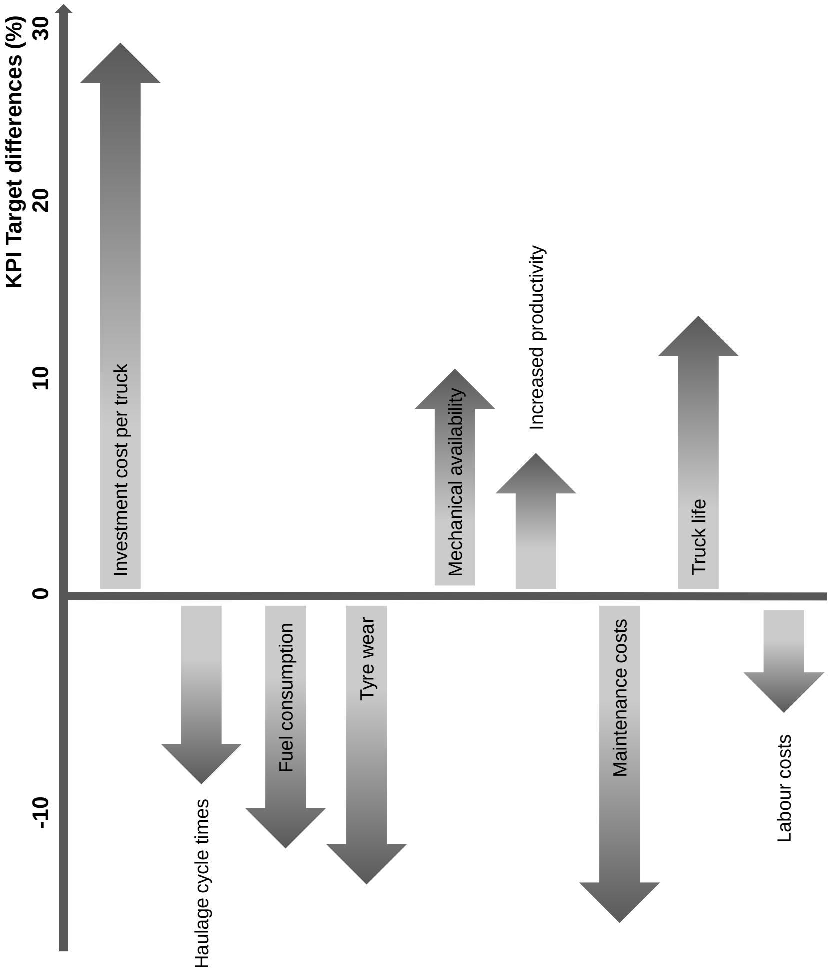

Fig 2. Estimated change to haulage KPI’s associated with autonomous haulage trucks

Looking further into the future of haulage units specifically, Albanese and McGagh (2011) see an ‘unconstrained’ driverless vehicle, uncoupled from the requirements to house and inform a driver of the truck’s location, operations and interactions in the mining environment. A truck that is more ‘symmetrical’ allowing multi-directional travel, all-wheel steering and drive systems with power- and energy-storage systems on-board under-body. This ideal combination of market-pull and manufacturer-push is leading to some of the new concept vehicles being either hypothesized or proposed currently, two examples of which are shown in Figure 3. Much has been made of the concept and developmental requirements of the autonomous truck itself (Nebot, 2004), but to date little attention has been made to what that truck runs on, in terms of mine road design and management, and how this needs to evolve in tandem with the trucks themselves.

Fig 3. Conceptual haulage truck developments; Komatsu AHT (above left, after Carter, 2011) and ETF Mining Trucks (above right, after ETF, 2011)

In all of the approaches discussed above, the decision to implement an AHS in a mine requires a thorough evaluation of impacts, not only operational improvements, but the inter-connectivity of this autonomy technology to other organizational processes. Lewis, Werner and Sambirsky (2004) noted that autonomous haulage has the potential to shatter the existing environment paradigms such as pit, haul road, and equipment design. Parreira and Meech (2010) are analysing the behaviour of this new technology in terms of variations in adaptability and utilization due to changes in various sub-systems or external environments, as a route to understanding the full interactions that may affect autonomous truck behaviour. Key amongst these agents/environments are haul road conditions and operating performance.

Mine Road Design State of the Art

The operating performance of a mine haul road can be subdivided into four distinct design components, following Thompson (2011). These design components have been derived from the historically empirical approach to mine road design, wherein an operating road is often incrementally improved until a satisfactory standard of performance is eventually achieved.

When designing and constructing a haul road for optimal performance, these design components are best addressed using an integrated approach, where specific design activities apply to each category and optimization takes place during design, as opposed to the operational phase of the road. If one design component is deficient, the other components may not work to their maximum potential and road performance is often compromised. The cure, however, is not necessarily just ‘more frequent maintenance’; no amount of maintenance will fix a poorly designed road. Figure 4 illustrates such an integrated approach, based on the geometric, structural (layerworks), functional (wearing course) and maintenance management components. As a precursor to evaluating the challenges and technological enhancements that road design can contribute to autonomous truck haulage systems, design activities for current haul road systems are described.

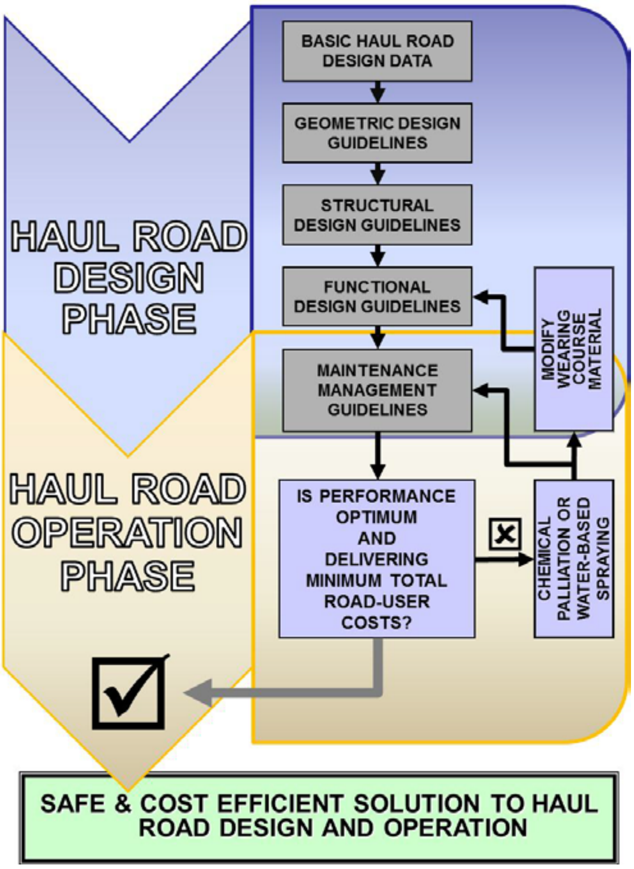

Fig 4.   Typical haul road design methodology associated with conventional mine truck haulage systems

Geometric Design

The geometric layout of a mine haul road is dictated to a great extent by the mining method used, structural geology and the geometry of both the mining area and the orebody. The road layout – or alignment, both horizontally and vertically is generally the starting point of the geometric design. Practically, it is often necessary to compromise between an ideal layout and what mining geometry and economics will allow. Broadly speaking, safety and good engineering practice require haul road alignment to be designed to suit all vehicle types using the road, operating within the safe performance envelope of the vehicle, or, where this is not possible, at the speed limit applied. Ideally, geometric layout should allow the vehicles to operate at their maximum safe speed, but since the same road is used for laden and unladen haulage, there is often the need to minimize laden travel times, through appropriate geometric alignment, whilst accepting compromise (generally in the form of speed limits) on the unladen return haul. The alignment issues to be considered to fully specify the horizontal and vertical alignment and layout of a haul road are listed below (Vagaja and Thompson, 2010);

- Vertical alignment issues:
    - Sight and stopping distance limits of truck;
    - Overtaking and safe following distances;
    - Ramp gradients.
- Horizontal (longitudinal) alignment issues:
    - Width of road;
    - Curvature, switchbacks, curve super-elevation (banking) and run-in run-out;
    - Cross-slope or camber;
    - Intersection layout;
- Combined alignment
- Safety berms, drainage design and roadside furniture

Suffice to say that as geometrical design constraints change to accommodate the full potential of AHS trucks, the response of the road, in terms of structural, functional and maintenance can also be expected to change. The impact of this change on operating performance is an unknown quantity. For instance, steeper roads (>10% grade) are not commonly encountered together with ultra-class trucks, and when combined with multiple-wheel drives and channelized traffic, theoretical knowledge of these effects is poor and empirical experience is of limited applicability.

Haul Road Structural Design

Haul roads deteriorate with time due to the interactive effort of traffic load and specific subgrade and in-situ material strengths and structural thicknesses. The CBR method (USBM, 1977, Thompson, 2011) has been widely applied to the design of mine haul roads in which untreated materials are used. However, when multi-layered roads are considered in conjunction with a base layer of selected blasted waste rock, a mechanistic approach is more appropriate, as described by Thompson (2011a). When a selected waste rock layer is located under the wearing course, road performance is significantly improved, primarily due to the load carrying capacity of the waste rock layer which reduces the susceptibility of the soft sub-grade and in-situ to the effects of high axle loads. Irrespective of the design methodology, the road as a whole must limit the strains in the sub-grade (in-situ) to an acceptable level and the upper layers must in a similar manner protect the layers below. Using this premise, the road structure should theoretically provide adequate service over its design life. Operating experience with ultra-class trucks has enabled reliable estimates of these limiting strain criteria to be made. However, with AHS and the associated different wheel loads and geometric configuration, coupled with channelized wheel paths and very likely poorer quality in-situ and road building materials, our knowledge of road structural performance is limited to a very few trolley-assist applications, whose mode of operation comes closest to what may result from AHS (in terms of channelization and wheel loadings), but material performance estimates would not be generically applicable.

Haul Road Functionality and Deterioration

Equally important as the structural strength of the design, is the functional trafficability of the haul road. This is dictated to a large degree through the selection, application and maintenance of the wearing course (or road sheeting) materials. Poor functional performance is manifest as poor ride quality, excessive dust, increased tyre wear and damage and an accompanying loss of productivity. The result of these effects is seen as an increase in overall vehicle operating and maintenance costs.

The functional design of a haul road is the process of selecting the most appropriate wearing course material or mix of materials, typically natural gravel or crushed stone and gravel mixtures that are commensurate with safety, operational, environmental and economic considerations. Typical specifications for wearing course material selection are described by Thompson and Visser (2006), based on operating performance requirements of convention as opposed to AHS applications (the latter may employ very different vehicle configurations and geometric design, which would require a different 'response' from the wearing course or sheeting). More-over, as mining moves to areas of thicker weathered, transported or regolith cover, suitable material for sheeting may not be readily available, and recourse must be made to some form of improvement-treatment.

Haul road dust palliation is often required when a sheeting fails to meet performance requirements. The motivation for the use of some additional agent to reduce a material's inherent erodibility is based on increasing particle binding. The finer fraction, although contributing to cohesiveness, also generates much of the dust, particularly when the material is dry. The presence of larger fractions in the material will help reduce erodibility of the finer fractions, as will the presence of moisture, but only at the interface between the surface and the mechanical eroding action. This forms the basis of the water-based dust suppression techniques used most commonly on mine haul roads. When chemical-based dust suppressants or stabilising agents are applied to an appropriate wearing course, an evaluation is required with which to determine the extent of the costs and benefits attributable to chemical-based suppression or stabilisation, together with an indication of those factors likely to alter the trade-off between improved and non-improved wearing course materials.

Haul Road Maintenance Management

Design and construction costs for the majority of haul roads represent only a small proportion of the total operating and road maintenance costs and in particular, the use of an appropriate road maintenance management strategy has the potential to generate significant performance improvements – particularly in the light of rolling resistance increases due to the interactive effects of traffic volume and wearing course deterioration (Thompson, 2011a).

Routine maintenance is carried out on mine haul roads almost daily, depending on the functionality of the road and the traffic volume. The principal goals are;

- To restore the road functionality to a level adequate for efficient vehicle travel with the aim of augmenting productivity and minimizing total road user costs
- To conserve the integrity of the road wearing course by returning or redistributing the gravel surface.

Ad-hoc or scheduled blading is an inefficient means of road maintenance, with the potential to generate excessive costs due to over- or under maintenance of the road. Ideally, an optimized approach is required with which to minimize total road-user costs, typical of the maintenance management system (MMS) for mine haul roads, following Thompson and Visser (2003). However, the MMS depends to a great extent on deterioration rate modelling, coupled with and assessment of the cost (direct and indirect) and benefits from maintenance itself. More work is required to assess road deterioration and defect progression rates and the optimum maintenance or rehabilitation frequency, as a precursor to a life-cycle cost model for AHS roads – cheap to build, expensive to operate and maintain, versus expensive to build, cheap to operate and maintain.

Road Design Case Study

Using the foregoing discussion as a basis for a simple comparative case-study, a road design is required for an AHS running ultra-class mining trucks of 624t gross vehicle mass (GVM). In this application, a daily tonnage of 200kt is hauled.

Using the CBR cover-curve design methodology for the structural layerworks (Thompson, 2011a), results in 2460mm of layerworks (Figure 5 (RHS)). However, this design approach will not easily accommodate the likely increase in channelised traffic associated with AHS and in addition, is not well suited to road design for the ultra-class truck. Using the more appropriate mechanistic design methodology described earlier, by incorporating a base layer of selected blasted waste rock above in-situ, the layerworks can be reduced to 850mm and the longer-term structural performance of the road is improved (Figure 5 (LHS)). This approach is, however, critically dependant on present-day experience with the limiting design criteria and as AHS develops, it may be anticipated that the associated limiting design criteria would be subject to re-assessment.

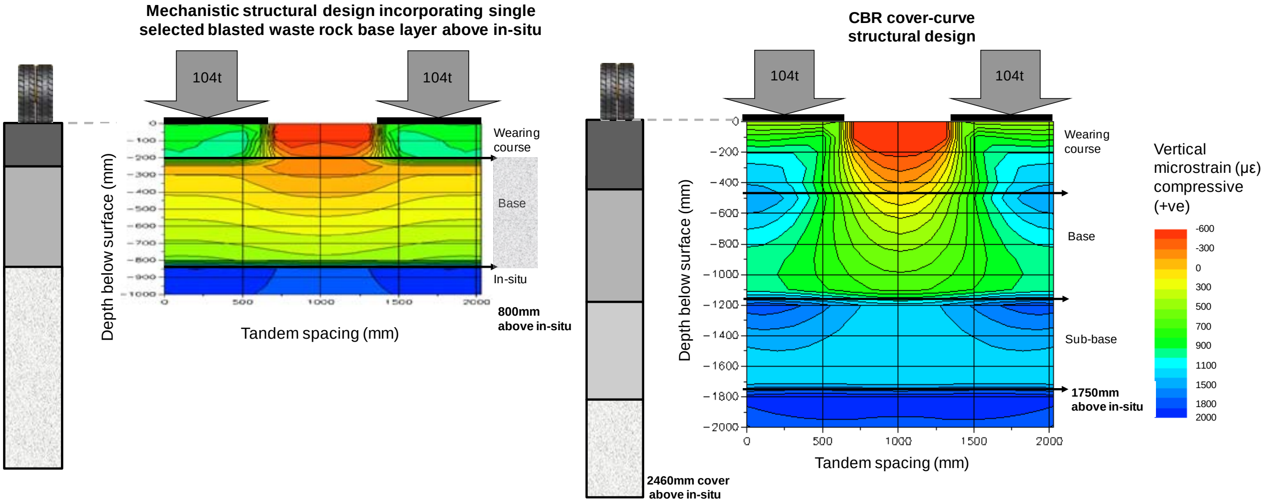

Fig 5.   Comparison of mechanistic structural design (LHS) and CBR (RHS) equivalents using 104 metric ton wheel load.

Turning to the wearing course or functional design aspects, an example is shown in Figure 6 of the rate of increase in rolling resistance as a function of the interval between road maintenance (blading/scraping) for a poorly selected wearing course material, subject to traffic volumes of 200kt/day. If an improved wearing course material is defined as part of the design process, significant reductions in rolling resistance can be achieved whilst at the same time, extending maintenance intervals on the road and reducing overall road deterioration rates. Again, it is critical to recognise the limitations of the fundamentals used in developing this model – specifically material types used and traffic volume limitations, and the validity of extending this approach to AHS.

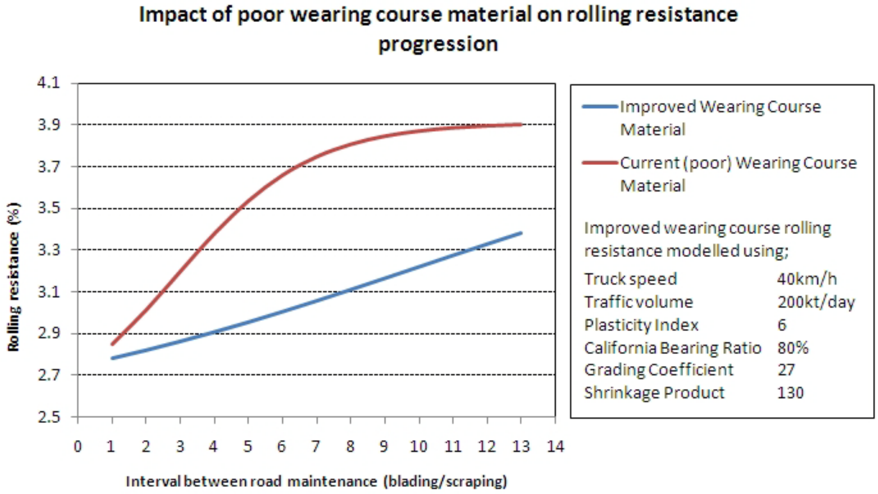

Fig 6. Impact of poorly-selected wearing course (sheeting) material on haul road rolling resistance deterioration compared to well selected material using current mine road material performance models.

Both of these example case-studies highlight the importance of both the design methodology adopted, and critically, the underlying assumptions of the fundamental approach to mine road-building and material performance models, together with the associated road management and performance optimization requirements for AHS.

ROAD DESIGN CHALLENGES FOR AUTONOMOUS HAULAGE AND MINING

The mine road design methodology shown in Figure 4 forms the basis of the road design requirements and enhancements for mines of the future, in which AHS may predominate. From Hustralid, Albanese and McGagh and Pukkila and Sarkka's work, it is clear that an incremental approach is an appropriate means of meeting these challenges, and will allow mine road design technology to mature at the same rate as the AHS evolves. In terms of the research foundation required to meet these challenges, a near (1-3 years), intermediate (4-10 years) and long-term (11-20 years) research framework is required (in addition to on-going problem-solving 'tactical' research in mine road design and management);

- Near-term research; to generate immediate solutions to design challenges that exist within the current available technology or systems, and the identification of longer-term, more complex issues which would inform intermediate- and long-term needs;
- Intermediate-term research; to solve problems of greater complexity, identifying long-term opportunities fundamental systematic and technological changes;

- Long-term research; required to explore innovative solutions or far-reaching fundamental systematic and technological changes.

The emphasis of mine road design, construction and management research for the past 20 or more years has largely been on short-term needs. These improvements have not been matched by improvements in the fundamental technologies of mine road design and management, and although the quality of mine roads have probably increased as a result, many fundamental and longer-term issues have yet to be addressed; universal approaches to road life-cycle cost modelling, mine road-building material performance models, road management and performance optimization, etc. Considerable research and innovation is required, from short-term tactical solutions to longer-term strategic systematic and fundamental technology and application improvements.

Increased mine truck traffic volumes and gross vehicle mass (GVM) has itself generated significant design challenges, especially when coupled with poor-quality road building materials (new surface mines in regions of thick regolith, weathered or transported material) and very immature applications of potential remediating technologies (geo-fibres, geo-textiles, polymers, stabilization, etc.). This has significantly increased pavement maintenance and rehabilitation costs, or where these activities are absent, resulted in increased total road-user costs. Construction practices and materials used in most mine roads will not provide adequate nor predictable performance in the presence of autonomous haulage systems. This situation will be aggravated if any of the environmental variables themselves (i.e. road geometry, vehicle speeds, GVM, materials, climate, etc.) depart further from what is known or experienced currently.

By analysing some of the key variables associated with autonomous haulage systems, a first indication of the road design future needs can be hypothesised. Listed below are these generic needs and considerations, from near-term 'tactical' considerations, through to long-term needs of a more strategic nature.

- In the near-term, autonomous haulage systems deployment would require;
  - Assessment and documentation of 'as-built' conditions of the road, as a benchmark for performance and deterioration modelling;
  - A real-time determination of road deterioration rates and locations;
  - Condition-triggered maintenance interventions;
  - Impact of channelized traffic on structural design requirements to be assessed;
  - Rapid structural capacity determinations to be facilitated;
  - Assessment of surfacing material functional performance limits;
  - A mature understanding of the impact of climate on road performance and availability, and associated all-weather operating surface requirements.

- In the intermediate-term, consideration should be given to;
  - How to automatically gather and assess road performance and distress data survey;
  - Using distress/condition survey data as basis for performance predictions and maintenance/rehabilitation planning;
  - Linking road performance data from various mine-sites to provide better regional predictive capabilities;

  - Developing a comprehensive approach to road rehabilitation design;
  - The impact of potentially steeper roads (>10% grade) on road and material performance;
  - The impact of narrower roads and channelized traffic on scheduled maintenance and rehabilitation;
  - Developing a better understanding of mine road life cycle costing and performance prediction techniques;
  - Relating road performance to truck damage, life-cycle costs and total road-user costs;
  - Evaluating the effect of maintenance strategies on road life, life-cycle costs and performance.

- In the intermediate-long terms, the use of autonomous haulage systems in new un-explored geological domains, areas of thick regolith/weathered/transported material cover, with no road-building data or experience, is likely and would require;
  - Regional road-building material engineering characteristics data-base;
  - Road performance and distress or degeneration rates models;
  - Road life-cycle costing modelling (build, operate and maintain).

- Finally, looking towards autonomous construction and maintenance/rehabilitation of the mine roads themselves, this would build on the near- intermediate- and long-term goals and would additionally require;
  - Strategies to asses in real-time and to modify or improve poor-quality road building materials (structural and functional design) specifications to align them with road-building requirements;
  - Rapid determination of ‘as-placed’ and ‘as-built’ conditions to determine correction construction (placement and compaction) requirements;
  - Interrogation of road performance and distress data to identify underlying design deficiency and appropriate remediation strategy;
  - Correlating road performance to design, construction and other factors, to improve predictive capability of performance and cost models.

Roadmap for haul road design and management

Figure 7 shows a summarized version of the broad generic challenges in road design development for AHS, from near-term ‘tactical’ considerations, through to long-term needs of a more strategic nature. The first theme is materials for road construction, design requirements, engineering specifications, performance limitations and strategies for improvements or enhancement of inherently poor or unsuitable materials. Allied to the materials themselves is the road management system aspects of maintenance and rehabilitation; specifically the requirement to predict and manage road maintenance and rehabilitation activities within the constraints of an AHS. Finally, total road-user cost and life-cycle cost modelling combines with the other themes to enable an optimal design and operational strategy to be determined. Strategically, these themes would ultimately lead to a technology target specifying the road design requirements for autonomous vehicle themselves, and ultimately, to the autonomous mine in which road construction, management and maintenance or rehabilitation is achieved autonomously.

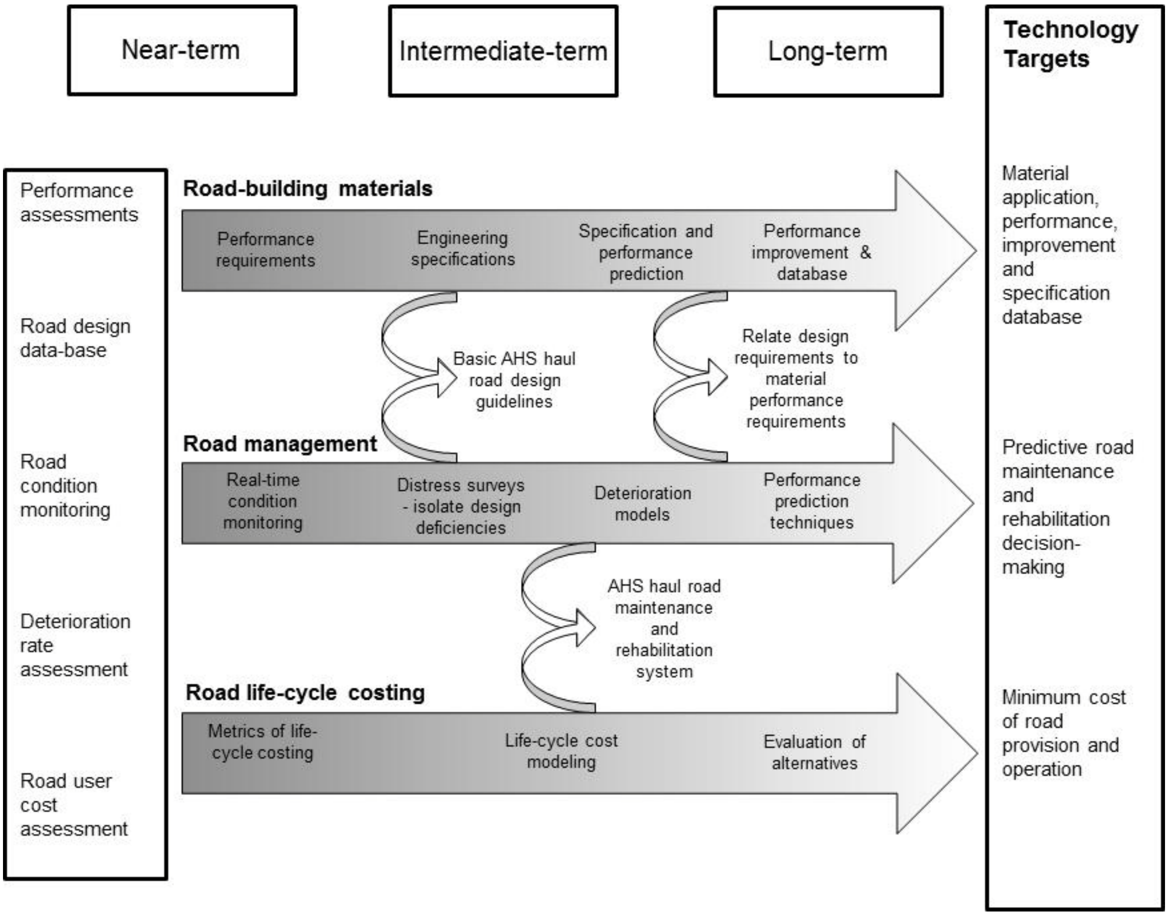

Fig 7. Roadmap for technology targets associated with autonomous haulage systems

CONCLUSIONS

The emphasis of mine road design, construction and management research for the past 20 or more years has largely been on short-term tactical needs. These improvements have not been matched by improvements in the fundamental technologies that underpin mine road design and management, and although the quality of mine roads have probably increased, many of fundamental and longer-term issues have yet to be addressed.

With autonomous haulage systems moving from pre-prototype to production-ready applications, any decision to implement these systems in a mine requires a thorough evaluation of impacts, not only operational improvements, but the inter-connectivity of this autonomy technology to other organizational processes. In developing an understanding the full interactions that may affect autonomous truck behaviour due to changes in various sub-systems or external environments, haul road conditions and operating performance is a key consideration. This is as true in autonomous as well as in conventional mine truck-based hauling systems where the mine haul road network is a critical and vital component of the production process.

The operating performance of a mine haul road can be subdivided into four distinct design components, derived from the historically empirical approach to mine road design, wherein an operating road is often incrementally improved until a satisfactory standard of performance is eventually achieved. This approach is inappropriate for autonomous haulage system operations and this paper has outlined some of the research and technology themes associated with improved mine road design and management systems, in the near

(1-3 years), intermediate (4-10 years) and long-term (11-20 years), in addition to on-going problem-solving ‘tactical’ research requirements in mine road design and management.

The first theme is materials for road construction, design requirements, engineering specifications, performance limitations and strategies for improvements or enhancement of inherently poor or unsuitable materials. Allied to the materials themselves is the road management system aspects of maintenance and rehabilitation; specifically the requirement to predict and manage road maintenance and rehabilitation activities pro-actively within the constraints of an autonomous haulage system. Finally, total road-user cost and life-cycle cost modelling combines with the other themes to enable an optimal design and operational strategy to be determined. Strategically, these themes would ultimately lead to a technology target specifying the road design requirements for autonomous vehicle themselves, and ultimately, to the autonomous mine in which road construction, management and maintenance or rehabilitation is achieved autonomously.

REFERENCES

Albanese, T and McGagh, J. 2011. Future trends in mining. In: *SME Mining Engineering Handbook. Ed. Darling*. Society for Mining, Metallurgy and Exploration, INC (SME), Lyttelton, Co. USA.

Carter, P. 2011. The intangible business case: autonomous hauling systems. *Mining Media International Haulage and Loading Conference* , Phoenix, Az. USA., pp21-38.

Emirates Truck Factory (ETF). 2011. ETF Mining Trucks. Available from: http://etftrucks.nl.vedor.com/Pictures/ [Accessed June 2011)

Hustralid , WA and Nilsson, J.-O. 1998. Automation and productivity increases at LKAB, Kiruna, Sweden . *Proc. CMMI Congress 1998*, Montreal, Canada.

Lewis, MW, Werner, J and Sambirsky, B. 2004. Capturing unrealised capacity. *CIM Bulletin*, 97:1076, ProQuest Science Journals, Montreal, Canada, pp57-62.

Nebot, EM. 2007. Surface mining: main research issues for autonomous operations. *Robotics Research*, STAR publication No. 28, Springer-Verlag, Berlin, Germany, pp268-280.

Parreira, J and Meech, J. 2010. Autonomous vs manual haulage trucks - how mine simulation contributes to future haulage system developments. *CIM Meeting 2010*, Vancouver-BC, Canada.

Pukkila, J and Sarkka, P. 2000. Intelligent mine technology program and its implementation. *Proc. Massmin 2000*, Brisbane, Australia.

Thompson, RJ and Visser, AT. 2003. Mine haul road maintenance management systems. *Jnl. of the South African Institute of Mining and Metallurgy*, 103:5, pp303-312.

Thompson, RJ and Visser, AT. 2006. Selection and maintenance of mine haul road wearing course materials. *Trans(A) (Mining Technology) Institute of Mining, Metallurgy and Materials (IMMM).* 115:4, pp140-153

Thompson, RJ. 2011. Building better haul roads. *Engineering and Mining Journal*, Mining Media International, June 2011, pp48-53.

Thompson, RJ. 2011a. Design, construction and management of haul roads. In: *SME Mining Engineering Handbook. Ed. Darling*. Society for Mining, Metallurgy and Exploration, INC (SME), Lyttelton, Co. USA., pp957-976

USBM. 1977. The design of surface mine haul roads - a manual. *USDOI Bureau of Mines IC 8758*.

Vagaja, D and Thompson, R. *Mining roads – safety and design*. ARRB/Curtin University WASM Public Workshop. 17-18 June 2010, Perth, WA.

FIGURE CAPTIONS

Fig 1 Incremental evolutionary phases of autonomous haulage and mining systems

Fig 2. Estimated change to haulage KPI's associated with autonomous haulage trucks

Fig 3. Conceptual haulage truck developments; Komatsu AHT (above left, after Carter, 2011) and ETF Mining Trucks (above right, after ETF, 2011)

Fig 4. Typical haul road design methodology associated with conventional mine truck haulage systems

Fig 5. Comparison of mechanistic structural design (LHS) and CBR (RHS) equivalents using 104 metric ton wheel load.

Fig 6. Impact of poorly-selected wearing course (sheeting) material on haul road rolling resistance deterioration compared to well selected material using current mine road material performance models.

Fig 7. Roadmap for technology targets associated with autonomous haulage systems

FIGURES

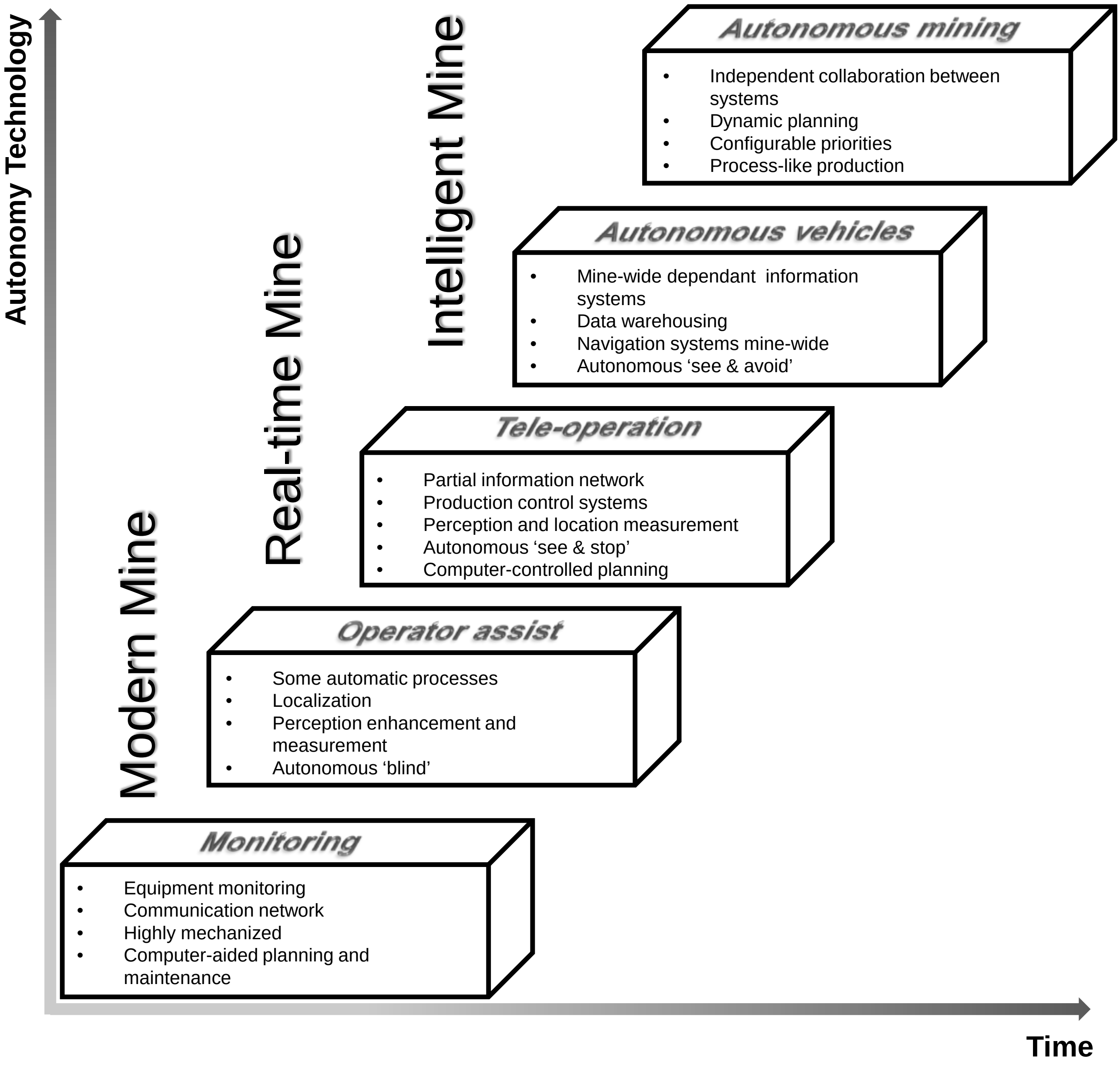

Fig 1 Incremental evolutionary phases of autonomous haulage and mining systems

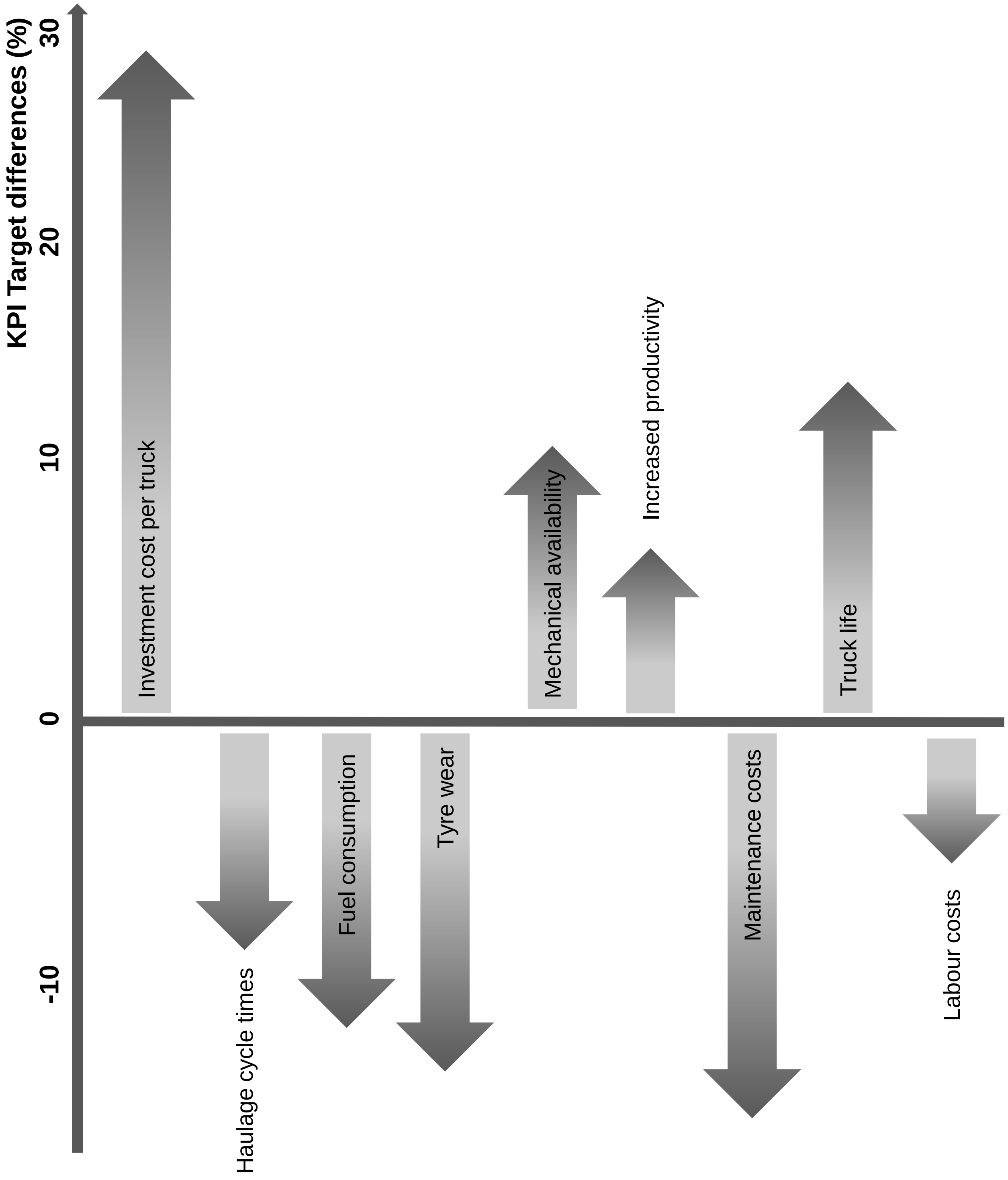

Fig 2. Estimated change to haulage KPI’s associated with autonomous haulage trucks

Fig 3. Conceptual haulage truck developments; Komatsu AHT (above left, after Carter, 2011) and ETF Mining Trucks (above right, after ETF, 2011)

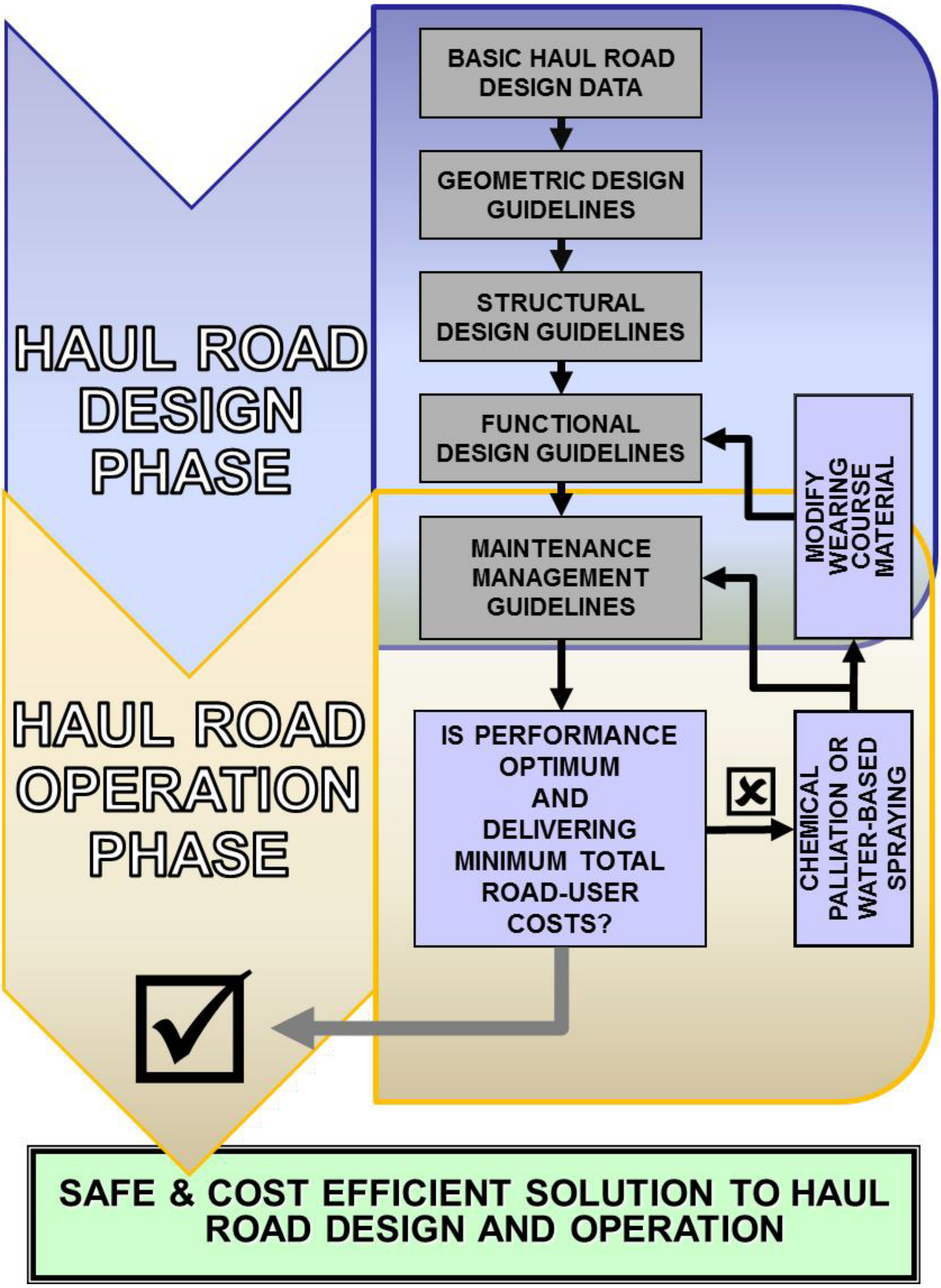

Fig 4. Typical haul road design methodology associated with conventional mine truck haulage systems

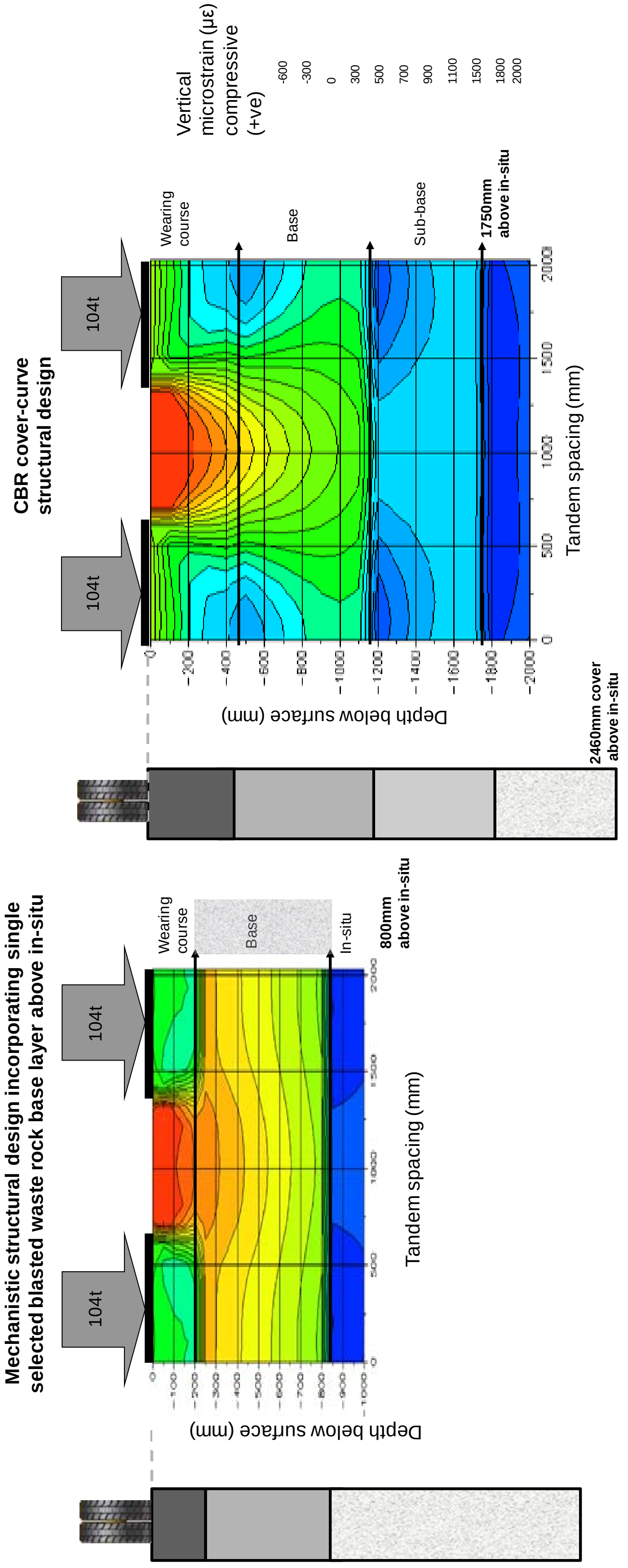

Fig 5. Comparison of mechanistic structural design (LHS) and CBR (RHS) equivalents using 104 metric ton wheel load.

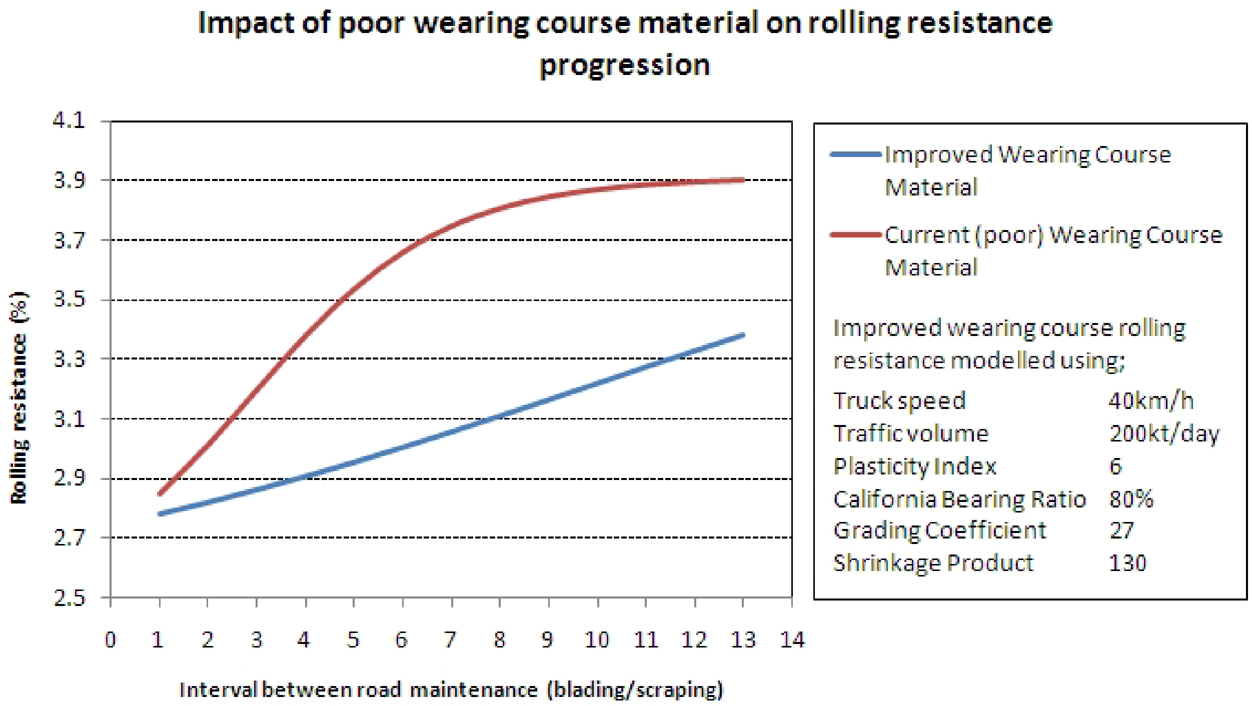

Fig 6. Impact of poorly-selected wearing course (sheeting) material on haul road rolling resistance deterioration compared to well selected material using current mine road material performance models.

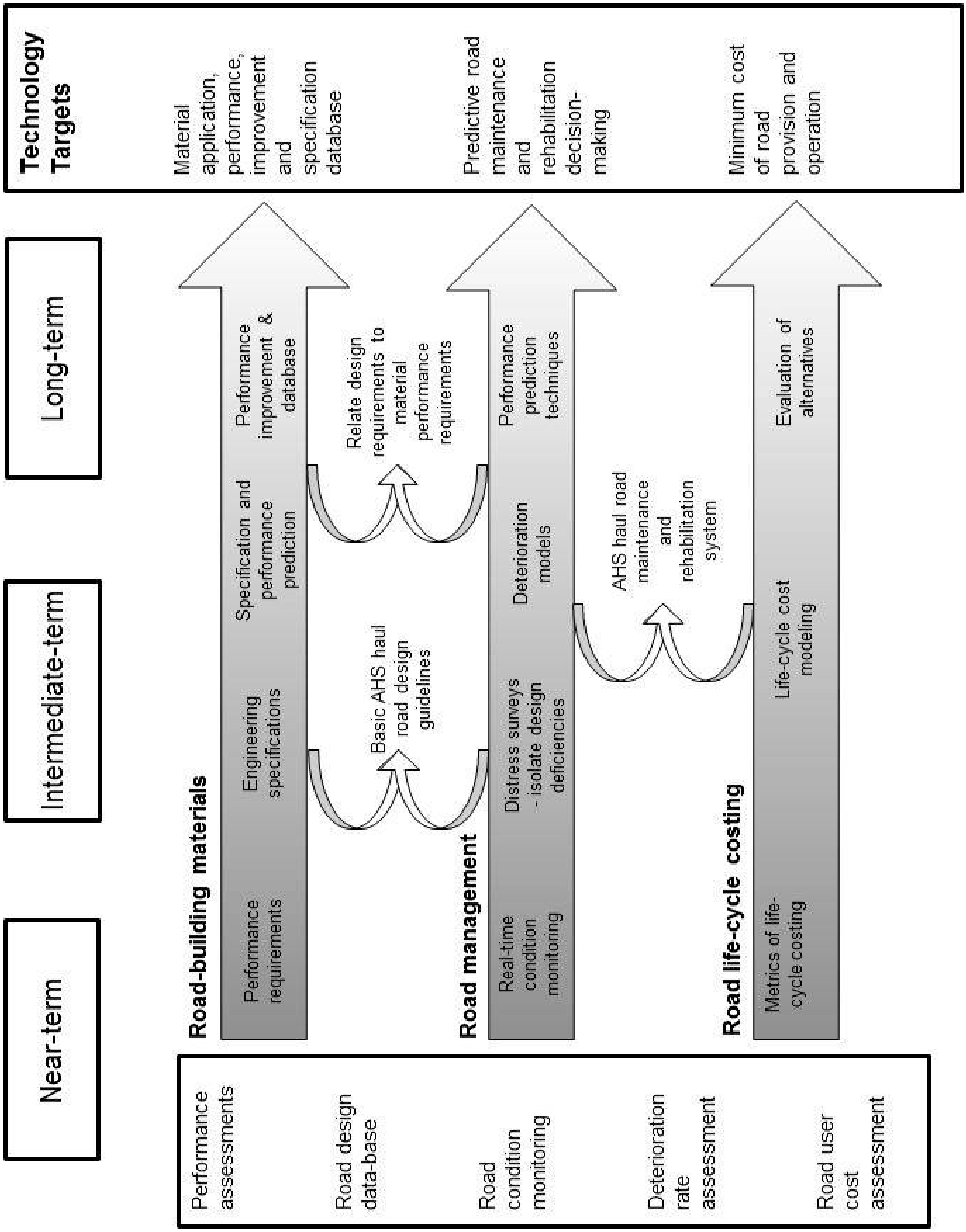

Fig 7. Roadmap for technology targets associated with autonomous haulage systems